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Design and development of a three-component force/moment sensor for underwater hydrodynamic tests

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ABSTRACT

In this paper, a three-component force/moment sensor is designed and constructed for underwater hydrodynamic force/moment measurements in water channel laboratory. First, an appropriate sensing structure to measure lift and drag forces as well as pitching moment is designed using finite element method (FEM). The sensing structure configuration and the corresponding dimensions are thus chosen so as to acquire acceptable sensitivity and negligible interference error amongst the components considering desired loading capacities. The appropriate locations of strain gauges on the hosted structure are found via the finite element analysis. The sensitivities of lift, drag and moment components are respectively estimated as 1.01 mV/V, 1.08 mV/V and 0.96 mV/V using FEM simulation. Finally, the experimental strain gauge-based three-component sensor is developed and calibrated. The experimental sensitivities of the sensor components are respectively measured as 1.04 mV/V, 1.15 mV/V and 1.00 mV/V for lift, drag and moment components through calibration tests. Besides, an interference error less than 2.25% is found amongst the sensor components. The experimental outcomes clearly reveal a very good agreement with the FEM simulation results through which the validity of the design procedure is affirmed.

1. Introduction

Force and moment are the most important mechanical quantities on which many other quantities as pressure and acceleration are based. The most fundamental law of mechanics is known to be the Newton's second law of motion which describes the effects of force and moments on the dynamics of rigid bodies. Accordingly, measurement of such important quantities is of practical importance in all engineering fields e.g., marine, aerospace, automation, control and robotics. The water channel laboratory is a very versatile facility which can be used to provide many useful experimental data for a wide variety of engineering problems in, for instance, the fields of oceanography, civil engineering and naval architecture [1]. Many hydrodynamic forces and moments can be measured experimentally in such hydrodynamic laboratory in order to verify the numerical results. Thus, the wide range of loads and the variety of problems likely to be encountered in such laboratories have suggested that there is a significant requirement for versatile types of multi-component dynamometers capable of being adapted for a specific problem. A multi-component dynamometer is a unit to simultaneously measure dynamic forces and moments in different directions. The main challenging problem concerning with the design of such multi-component force–moment sensors is to minimize the interference errors amongst the components (for the required loading capacities) as best as possible. Besides, acceptable sensitivity and accuracy should be obtained. The suitable size of the sensor as well as the corresponding working conditions would be another important design consideration. Therefore, designing such a multi-component dynamometer for a specific task is a challenging problem. Many researchers presented various multi-component force–moment sensors for different applications.

Millward and Rossiter [1] presented a multi-purpose multi-component strain-gauge based dynamometer for the water channel experiments. The presented dynamometer consisted of a series of unit blocks of different maximum capacities which could be assembled together into an appropriate configuration according to the required capacities of force/moment for each component. The design capacities of the force blocks ranging from 10 N to 0.5 kN as well as moment capacities of 50 Nm were considered. They utilized strain gauges which were already mounted on a backing plate and were simply welded in place due to their long term stability and ease of installation. Full bridge circuitry incorporating an excitation voltage of 4 V was used so as to have the maximum

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sensitivity as well as built-in temperature compensation. They reported a small interaction error and long term stability for their design. Molland [2] designed and constructed a five-component strain gauge dynamometer for wind tunnel tests. The maximum design loads for lift and drag elements were 756 N and 378 N respectively. On the other hand, the moment capacities about x-axis, y-axis and z-axis were respectively 463 Nm, 237 Nm and 136 Nm. A shear-type aluminum sensing structure along with full bridge strain gauge circuitry was employed for each component. A supply voltage of 7 V was chosen for each bridge which included 120 Ω strain gauges. The accuracy of the dynamometer was found to be ±1.2% of full scale (FS) for torque and ±0.4% FS for the remaining components. An acceptable repeatability characteristic as well as relatively small interaction was reported. Almeida et al. [3] proposed a ring-type strain gauge-based sensing structure to measure dynamic forces in wind-tunnel testing. They measured time series of force values and then translated into lift, drag and pitch moment. High quality results with acceptable dynamic characteristics (up to 25 Hz) were reported. The first natural frequency of the structure was 250 Hz which was ten times the maximum used frequency in the calibration stage. Other work about the application of strain-gauge based dynamometer in wind tunnels can be found in [4].

Joo et al. [5] described the design procedure of a compact six-component load cell for robotic applications using parallel plate structure (PPS). The maximum capacities for forces and moments were considered as 196 N and 19.6 Nm respectively. They employed FEM analysis to find the strain gauge locations so as to minimize the interference errors. A ring type structure was then added to the double PPS in order to increase the sensitivity of F_z component. The maximum interference and nonlinearity errors were 6.93% FS and 0.21% FS respectively. The natural frequencies of each force and moment component for the load cell were above 1.19 kHz and hence, it was suitable for robotic applications. Kim [6] designed a six-axis wrist force/moment sensor using FEM for robot arms. The significant importance of the work may be attributed to the fact that the intelligent robots should be able to safely grasp an unknown object which in turn required a compact force/moment sensor. Finally, an acceptable interference error less than 2.85% was reported from the experiment. Other work regarding the application of multi-component force/moment sensor for robotic application can be addressed in [7].

An effective method to design six-component force/moment sensors based on the application of binocular sensing structure was addressed by Kang et al. [8]. An intentional stress concentration technique similar to conventional industrial load cells was devised in the proposed sensing structure so as to increase the sensitivity. The structure dimensions were thus optimized by FEM analysis in order to find suitable strain distribution at the gauge locations. In addition, the influence of different structural dimensions on the strain distribution at the critical points was discussed and tabulated. The maximum capacities of the load cell were 196 N and 19.6 Nm for force and moment elements respectively. Finally, the interference error was found to be less than 2.5% FS. Kim et al. [9] designed and fabricated a column type multi-component force/moment transducer. The structural dimensions were first found analytically and later, verified by finite element analysis. A decoupling method based on addition and subtraction processes of signals obtained from strain gauges were proposed to reduce the interference error. As a result, the interference errors were found to be 7.3% FS for F_x component and 5% FS for the rest of components. Liu and Tzo [10] presented a novel six-component force sensor. They utilized four identical T-shaped bars as force sensing structure of the mentioned transducer. They applied FEM optimization to obtain maximum sensitivity. However, a significant interference error was reported for their design.

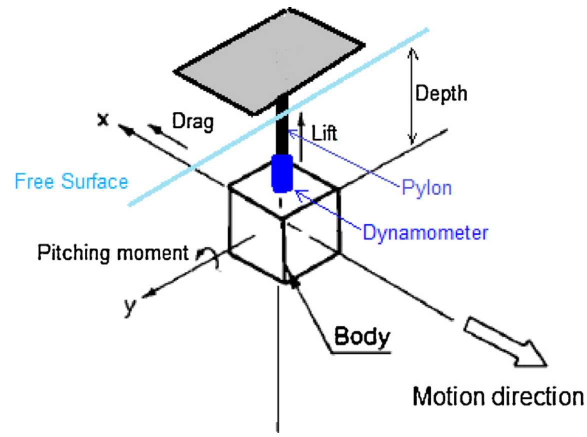

Fig. 1. Considered forces and moment affecting the underwater body in water channel.

This paper proposes a novel three-component strain gauge-based dynamometer for underwater force–moment measurements in water channel laboratory taking into account the design requirements. A complex binocular-like sensing element was introduced to simultaneously measure drag and lift forces as well as the pitching moment affecting the under water vehicle. First, a suitable sensing structure is designed and optimized using FEM analysis. The structural dimensions are thus chosen so that a negligible interference error as well as an acceptable sensitivity is acquired considering maximum loading capacity of each component. Besides, a compact configuration of the sensing element is presented to reduce the fluid–structure interaction. Then, the attachment locations of the strain gauges on the hosted structure are determined. Finally, the proposed three-component force/moment sensor is fabricated and the simulation results are verified through experimental investigations.

2. Design of the three-component force/moment sensor

2.1. Design requirement

As discussed earlier the dynamometer was required to be capable of measuring the drag and lift forces along with the pitching moment affecting the underwater vehicle as shown in Fig. 1. The maximum loading capacity for each component of the sensor was previously determined through CFD simulation according to the underwater body geometry and the maximum speed of 10 m/s. Hence, the maximum loading capacities of 300 N and 400 N were considered for drag and lift components respectively. In addition, the maximum capacity of pitching moment was considered as 100 Nm. It is obvious that the required moment to force ratio is significantly larger compared to other investigations done by Joo et al. [5], Kim [7] and Kang et al. [8]. Hence, their proposed sensing elements cannot be effectively employed for the current application. The maximum expectable weight of specimen was considered as 100 kg. One should keep in mind that the water channel contains two distinct sections, namely, dry and test sections. The scaled model is first attached to the pylon mechanism in the dry section (chamber) which is fully empty of water. Hence, just during the installation time in the dry chamber the lift component of the sensor will experience the full weight of the model (e.g., 100 kg at critical conditions). It is important to notice that this time period is temporarily and the sensor output is not considered at this section. However, the sensing element must be able to safely withstand this temporarily overloaded condition. On the other hand, after installing the model, the dry chamber is filled with water and the